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Investigation on the Fretting Wear of A coated Substrate with Interlayer

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Abstract. The fretting wear of coated SCMV (high-strength alloy steel) substrate with interlayer is studied with the focus on stresses associated with the coating failure under gross sliding condition. The analysis is simulated using finite element based method for a given number of cycles of worn half cylinder-on-flat geometry. The effect of interlayer stiffness on the stress distributions in the coating is studied. The maximum tensile stress at the trailing edge and the maximum compressive stress at the leading edge are reducing with increasing interlayer stiffness. The maximum shear stress at the coating-interlayer interface is predicted to have negligible effect with the change of interlayer stiffness. All the stresses are generally predicted to reduce with cycle. In general, stiffer interlayer will reduce the risk of coating failure.

Introduction

Fretting is a repeated cyclical small relative movement between two surfaces, in which over a period of time will remove material from one or both surfaces in contact. Fretting is a special case of fatigue wear at the surface, where the distance of reciprocating sliding is typically smaller than the contact length [1]. It can be categorized under two conditions, partial slip and gross sliding condition. Partial slip fretting occurs under high normal load and small displacement amplitude while gross sliding fretting occurs under low normal load and high displacement amplitude [2]. The response of partial slip condition normally associated with cracking of the surfaces while gross sliding fretting response is associated with wear of the surfaces. Main parameters which affect the fretting behaviour are normal load applied, coefficient of friction, and relative displacement of the contacting surfaces.

Fretting is a complicated process involving the effects of running conditions, environmental conditions and material properties. Since it is intimately related to wear, corrosion and fatigue, increasing the resistance against fretting is best accomplished by the application of surface modification methods. There are many surface modification methods which can be used to mitigate fretting damage. However, the mechanisms for the improvement are quite different. The four main mechanisms to enhance fretting resistance can be summarized as: to induce a residual stress; to decrease the coefficient of friction; to increase the hardness (to prevent adhesion and to increase abrasive wear resistance); to increase the surface roughness).

Coatings are widely used to control friction and wear in all kind of contacts and it is used in a wide range of mechanical engineering applications, particularly in tooling, engines, transmissions, and medical and food technologies. Usually, coating failure occurs when a protective coating does not live up to its expected service life and performance. Hard coated surfaces generally fail by through thickness cracking, delamination, spallation, and coating buckling [3, 4]. In some cases, interlayer is placed between the coating and the substrate. An interlayer has two functions which are to increase the bonding strength between the coating and the substrate and to reduce the interfacial intrinsic stress [5]. Interlayer also can accommodate the stresses at the coating or substrate interface. Therefore it is important to study the stress behaviour in the coating and its interaction with the interlayer with wear cycles.

FE modelling of coated substrate has been studied by Holmberg et al. [6] on the effect of coating's mechanical properties and thickness on its potential failure mechanism. Mohd Tobi et al. [7] incorporate the effect of wear on modelling fretting of coated substrate by simulating wear using an FE-based incremental wear simulation. They predicted failure by fracture in the coating is reducing with wear but shear delamination failure is predicted to increase with wear. In this paper, the stresses associated with the coating failure modes for a coated substrate with interlayer are studied using a FE based method. The effect of wear is simulated by taking the worn geometry profile from the work of [7]. The analysis is focussed on the effect of the interlayer stiffness to the stress distribution in the coating.

Finite Element Modelling

The finite element modelling is conducted by using finite element ABAQUS software version 6-10. The simulation is based on a two dimensional (2D) plane strain analysis to reduce computational time when combined with optimized mesh design. The flowchart of the modelling process is shown in Fig. 1. The geometry is based on half cylinder-on-flat contact configuration of [7]. The half cylinder is 6 mm in radius and the flat is 12 by 6 mm rectangular. Coating of 4 μm thick with an additional of 4 μm interlayer is modelled on both the cylinder and flat contact area for a width of 1.2 mm. The schematic view and its full FE model of the contact configuaration is shown in Fig. 2. Substrate modelled is SCMV (high-strength alloy steel) with Young's modulus, E of 200 GPa and Poison's ratio, v of 0.3. The coating's stiffness is 100 GPa and the material interlayer stiffness is in range of 50 GPa to 400 GPa with Poison's ratio, v of 0.2 for both the coating and the interlayer. Only linear elastic response is considered

Friction coefficient of 0.3 is assigned on the contacting surface. Normal load, P of 50 N/mm is applied at the centre on the top of the half cylinder and a cyclic x-direction displacement, δ^* of 17.5 μm is applied to the cylinder in the subsequent step for one complete cycle while constraining the bottom half of flat geometry in the x and y-directions. Linear constraint equations are employed to ensure uniform horizontal and vertical displacement for nodes on the top surface of the cylinder [7].

Plane strain and linear quadrilateral elements were used for mesh. The element dimensions in the coating layer and on the contact surfaces are 4 μm square. This gives a high degree of accuracy for the predicted stress field. Mesh sensitivity study has been conducted for mesh size of 1 μm, 2 μm and 4 μm square meshes and found that less than 10% difference in the stress gradient is predicted between 1 μm and 4 μm square meshes while significant reduction in simulation time is achieved with 4 μm mesh.

Excellent agreement is achieved between the FE model and the theoretical Hertzian solution [8] on contact pressure distribution of monolithic substrate under normal loading condition for the purpose of the FE model validation as shown in [7]. The unworn FE model predicted closely matched results as published data of [7] for the case of coated substrate with the interlayer stiffness of 100 GPa on the interface stresses distribution (e.g. for the case of E_c/E_s = 0.5 in [7], the maximum tangential stress predicted is around 120 MPa similar with the results from the current FE model. Five wear profiles are drawn at 0th, 10,000th, 20,000th, 50,000th, 100,000th and 200,000th cycles. The wear profiles data are taken from [7] which has been modelled at wear coefficient of $1.14x10^{-9}$ MPa^{-1} and by assuming that the interlayer has insignificant effect in altering the wear amount due to the contact become conforming under gross sliding condition.

Results and Discussions

The stresses of particular interest in this study are the tangential (tensile) stress, σ_{xx}, in the coating at the coating surface which associated with coating fracture, the tangential (compressive) stress, σ_{xx}, in the coating at the coating-interlayer interface, which associated with coating buckling delamination and the shear stress, τ_{xy}, in the coating at the coating-interlayer interface which associated with shear delamination of coating. The stresses are taken at the centroidal point of meshes on the coating surface i.e. 2 μm from the surface.

Stress Evaluation. In general, the trends predicted are similar with the work by [7]. The tangential (tensile) stress, σ_{xx}, at the coating surface and the tangential (compressive) stress, σ_{xx}, at the coating-interlayer interface are generally predicted to be reduced with fretting cycles (Fig. 3) .The Maximum compressive tangential stress is predicted at the contact leading edge while the maximum tensile tangential stress is predicted at the trailing edge of contact. For the shear stress, τ_{xy}, at the coating-interlayer interface however, a different trend is predicted compare to with the work [7] (Fig. 4). In this study the shear stress, τ_{xy}, at the coating-interlayer interface is predicted to reduce with cycle which contradict with the results presented in [7]. Comparing the results between the two, it can be seen that the results in this study doesn't be able to pick up high shear stress concentration on the leading edge of contact as in [7]. This might be attributed to the fact that for the current study the mesh constructed for worn profile geometry is a fresh mesh while the mesh for the worn profile of [7] is a condensed adaptive mesh (i.e. the mesh has been shrunk in size to accommodate the movement of the worn surface profile. This movement thus created a denser mesh which is able to pick up high shear stress concentration at the leading edge of contact. This behaviour will be addressed in other study by the author.

Effect of Interlayer Stiffness. On the effect of interlayer stiffness, it can be seen on Figs. 5 and 6 that both the maximum tangential (tensile) stress, $\sigma_{xx(max)}$, at the coating surface and the maximum tangential (compressive) stress, $\sigma_{xx(min)}$, at the coating interface are predicted to reduce with increasing interlayer stiffness. For example at 0^{th} cycle, the maximum tangential (tensile) stress, $\sigma_{xx(max)}$, in the coating at the coating surface reduces by as much of 30% when the interlayer stiffness changed from 50 GPa to 400 GPa. The explanation for this is due to the additional load bearing capability is introduced by the interlayer. Since the coating is relatively thin coating (i.e. the ratio of coating thickness to the contact semi width $t/a \sim 0.05$), the presence of the interlayer provides support from the load applied with stiffer coating provides greater load support and thus reducing the stresses in the coating itself.

The effect of interlayer stiffness on for the shear stress, τ_{xy}, at the coating-interlayer interface is less prominent (Fig. 7). As the contact worn and become conforming, stress distribution throughout the contact will be uniform thus lessen the role of interlayer as load bearer. Most stresses will be borne by the coating itself and thus insignificant effect of the interlayer on stress distributions. It is important to note that the high stress concentration at the leading edge of contact is not captured for the current study as discussed in previous section.

Conclusion

The current work illustrates the effectiveness of FE analysis as a tool to study the stresses associated with coating failure in a coated substrate with interlayer under normal and tangential loading with fretting wear effect. The present work focused on the effect of interlayer stiffness and changes of surface profile due to wear. The predictions lead to the following conclusions:

- The maximum tensile stress, $\sigma_{xx(max)}$ at the trailing edge and the maximum compressive stress, $\sigma_{xx(min)}$ at the leading edge are reducing with increasing interlayer stiffness.
- The maximum shear stress, τ_{xy} at the coating-interlayer interface is predicted to have negligible effect with the change of interlayer stiffness.
- Stiffer interlayer will reduce the possibility of fracture and buckling delamination on the coating.
- All the stresses and thus possibility of failure are generally predicted to reduce with wear cycles.

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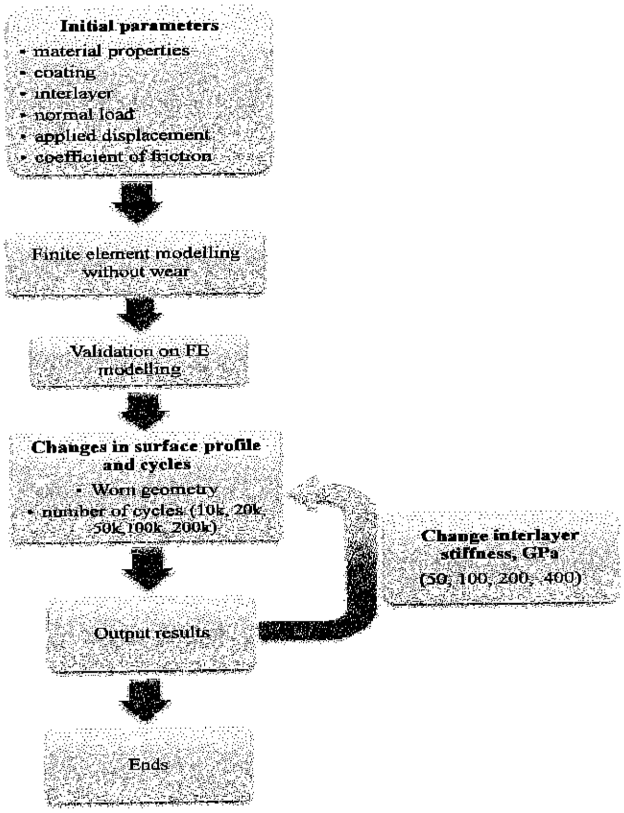

Fig. 1. Flowchart of the modelling process.

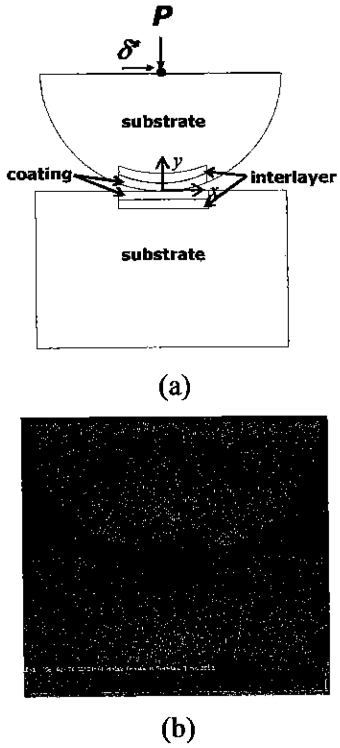

Fig. 2. Half cylinder-on-flat contact configuration: (a) Schematic view and (b) FE model (6 mm by 12 mm flat specimen).

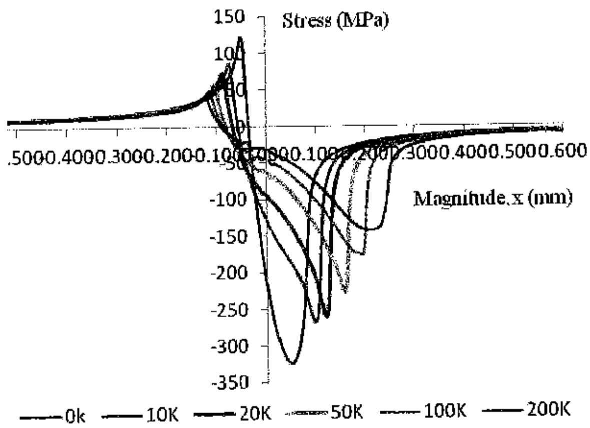

Fig. 3. Tangential stress distribution, σ_{xx} in the coating with 100 GPa Interlayer at end of contact sliding (Stress values are taken at 2 μm from the surface and the cylinder is sliding to the end right).

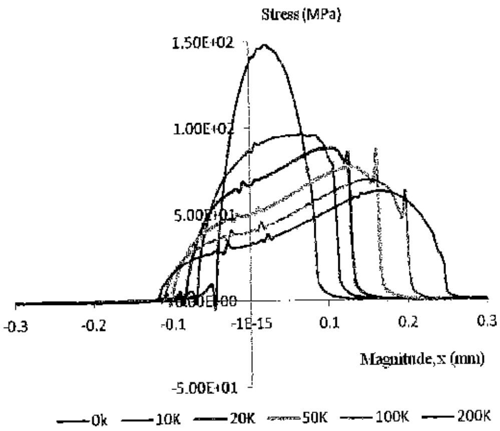

Fig. 4. Shear stress distribution, σ_{xy} in the coating with 100 GPa Interlayer at end of contact sliding (Stress values are taken at 2 μm from the surface and the cylinder is sliding to the end right).

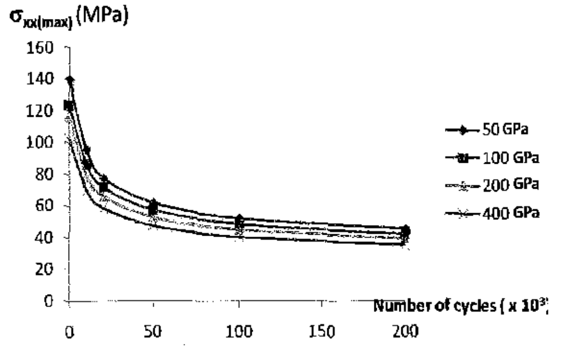

Fig. 5. Effect of coating interlayer stiffness on the predicted evolutions of maximum tangential stress in the coating, $\sigma_{xx(max)}$.

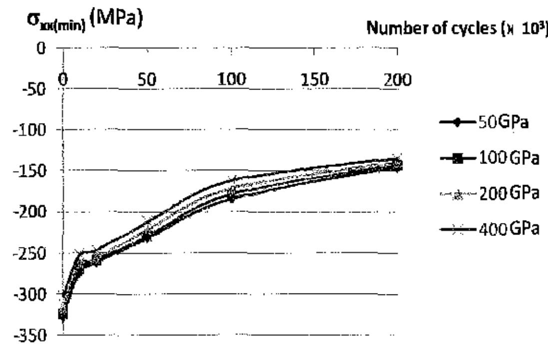

Fig. 6. Effect of coating interlayer stiffness on the predicted evolutions of minimum tangential stress in the coating, $\sigma_{xx(min)}$.

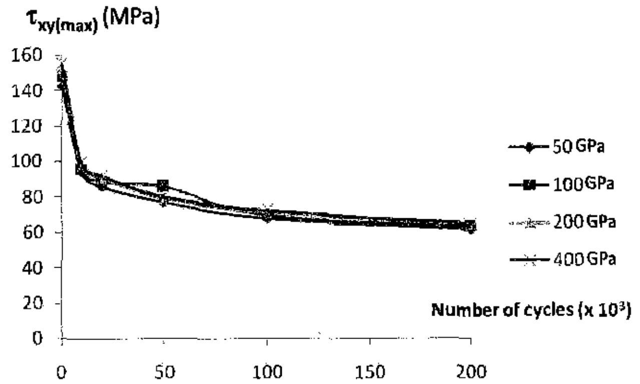

Fig. 7. Effect of coating interlayer stiffness on the predicted evolutions of maximum shear stress in the coating, $\tau_{xy(max)}$.

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